Plasma Reduction of Lunar Regolith for In-Space Fabrication

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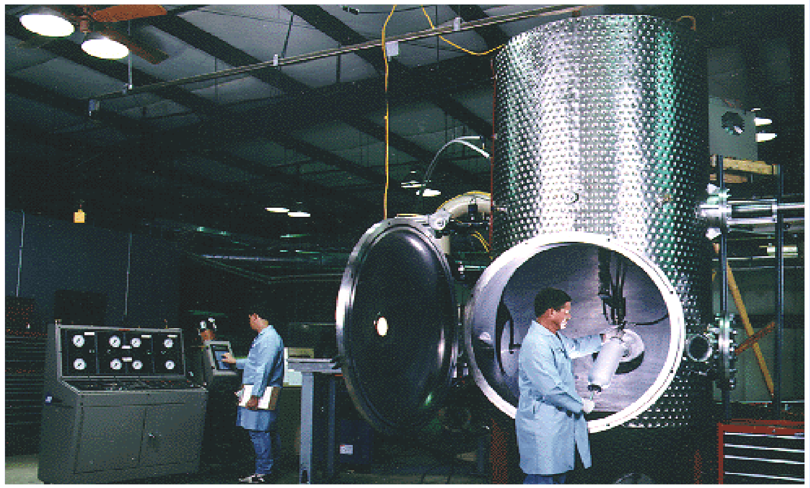
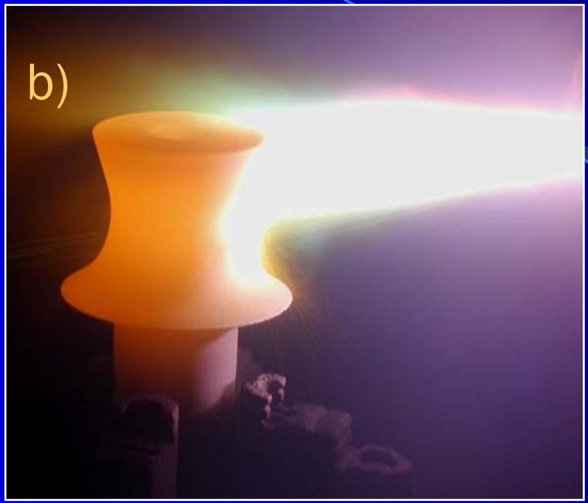
Contract No: NNM07AA23C
NASA SBIR Program Phase 2 Contract

Overview of Plasma Processes, Inc.

Plasma Processes, Inc is a ISO 9001:2000-certified small business specializing in the development and manufacture of high and ultra-high temperature materials, coatings, net-shape structures, and powder processing services.



VPS Manufacturing



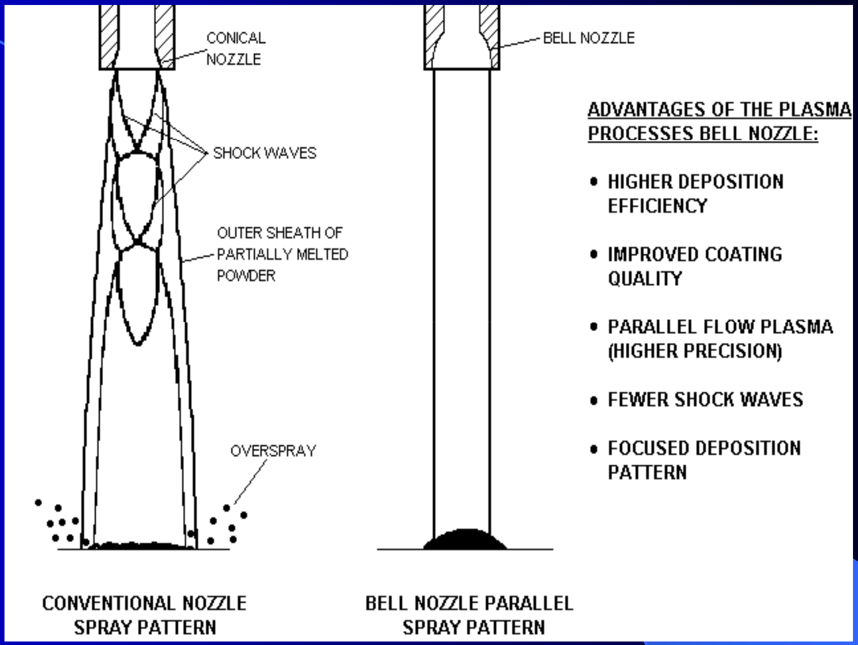
a) W non-eroding throat fabricated at PPI with a carbon diffusion barrier on the OD
b) W throat during VPS fabrication
c) Same throat after W deposition

Technical Profile:

1) Extremely high deposition rates; up to 15 lbs per hour
2) Thicknesses from 0.001 inches to 3.0+ inches
3) Largest VPS chamber can accommodate part 3.5' diameter x 6' high
4) 2 x VPS chambers online; 3rd in progress
5) Manufacture in inert atmosphere with choice of inert gases

Plasma Reduction Optimization

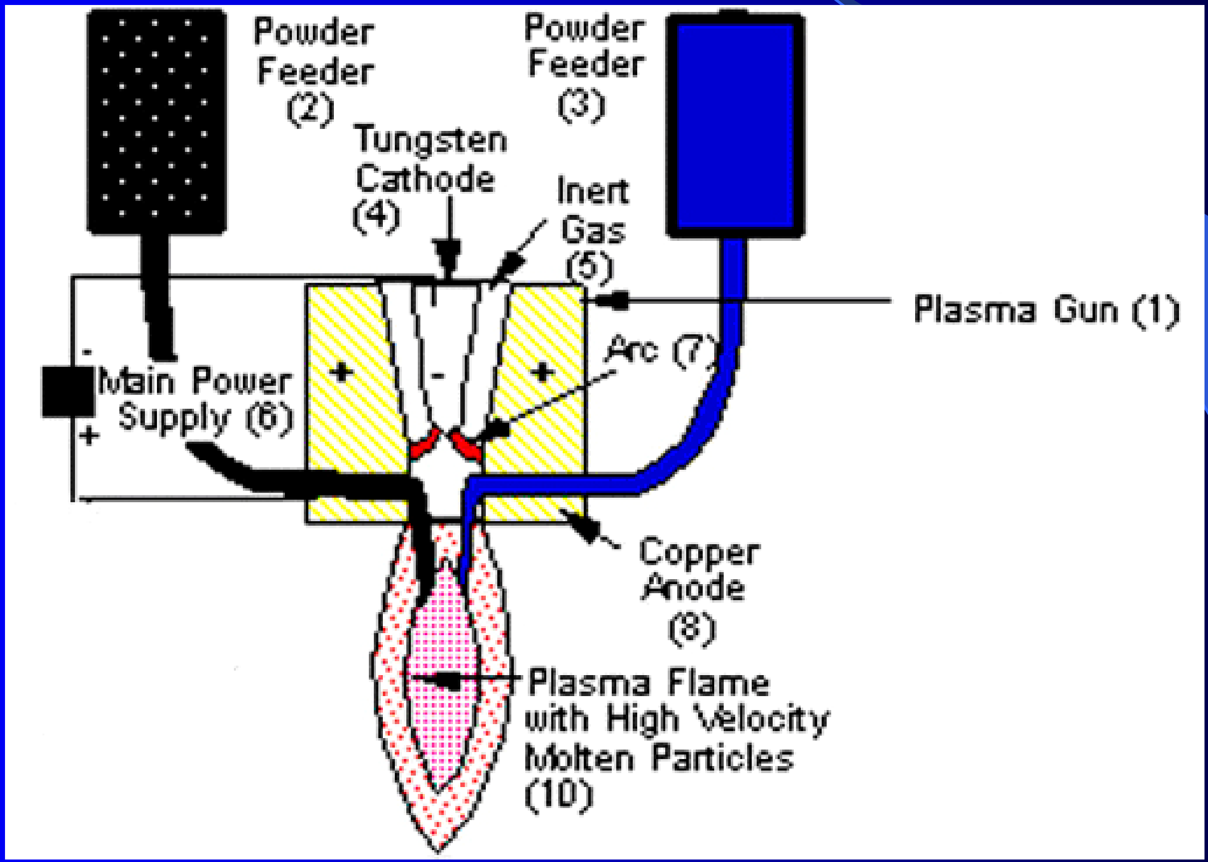
PPI Patented bell contoured parallel flow nozzles eliminate disruptive shock waves and expansion fans in plasma plume, providing ideally expanded plasma gas and collimated flow for better particle entrainment and spray characteristics.



Powder Alloying and Spheroidization℠ (PAS℠) Process

- Powder feedstock is fed into a plasma.
- Reaction between the plasma and feedstock results in melting/evaporation of the feedstock material.
- Droplets pass out of the plasma, rapidly solidify and are collected.
- Vacuum or inert atmosphere for oxygen sensitive materials, or ambient conditions.
- Auxiliary cooling gases enhance powder cooling.
- Argon plasma gas and hydrogen secondary gas typically used.

Plasma Reduction Experimental Setup



Significance of this Effort

- Raw materials (e.g., metals and O_2) are needed for in-space fabrication, life support, and fuel use.
- An innovative plasma reduction technique has been used to produce Si, Fe, & Mg metals and gases from JSC-1 lunar regolith simulant during Phase 1.
- During Phase 2, plasma reduction techniques are being optimized to produce pure O_2 and additional metals such as Al, Ti and Ca from regolith simulant.
- The development of these technologies are vital for long-term Lunar and Martian exploration.

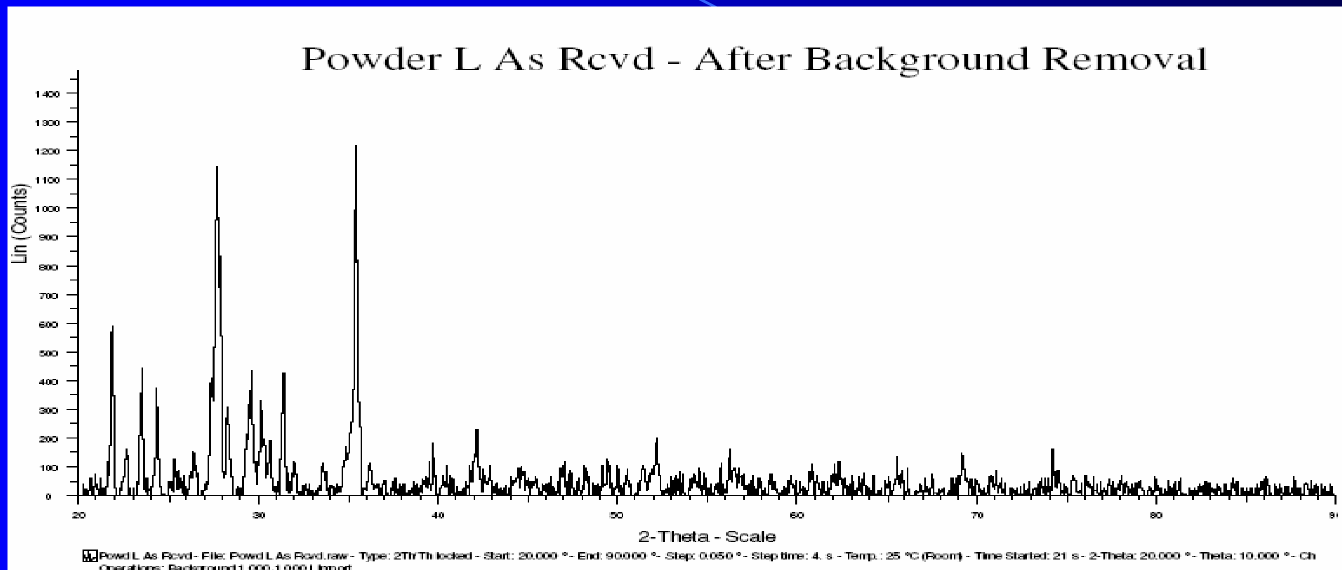
NASA and Non-NASA Applications of Phase 2 Technology

- O_2 (H_2O) for life-support, habitat and propulsion use
- Mature lunar simulant for dust, abrasion, mining & excavation research
- Metallic feedstock for in-space fabrication and rapid prototyping: Si - solar cells; Al, Ti, Fe - structural use

Other Applications:

Powder metallurgy products, protective coatings, catalysts, composite additives, sintering aids, microfiltration membranes, rocket fuel additives, rocket motors, electronics, fuel cell technologies

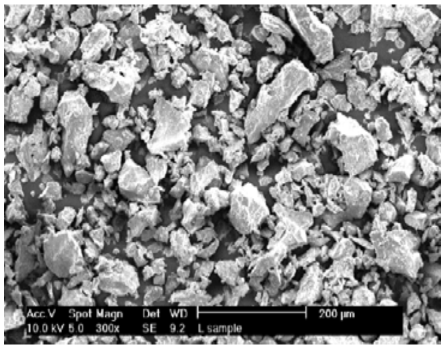
JSC-1 Lunar Regolith Simulant

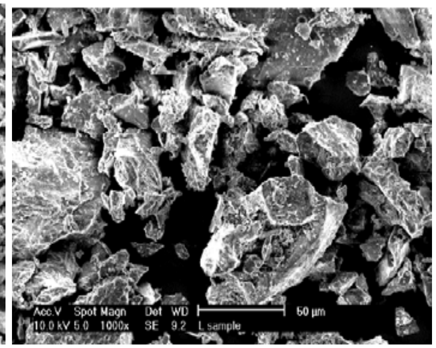


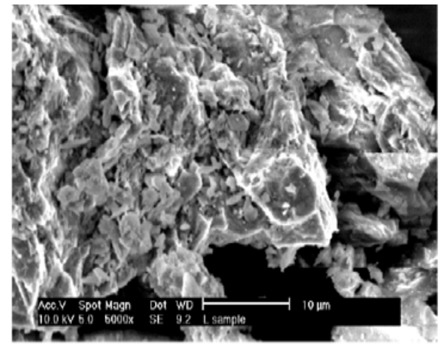
XRD analysis of As-received JSC-1 powder containing a complicated mixture of many minerals. Positively identified are albite ($NaAlSi_3O_8$) and anorthite ($Al_2O_3 \circ CaO \circ 2SiO_2$). Small amounts of magnetite (Fe_3O_4), akermanite ($2CaO \circ MgO \circ 2SiO_2$), oligoclase [$(Na,Ca)Al(Al,Si)Si_2O_8$], and labradorite ($Na_2O \circ 2CaO \circ 3Al_2O_3 \circ 8SiO_2$) might be present.

JSC-1 Lunar Regolith Simulant

As-Received Lunar Regolith Simulant (JSC-1)

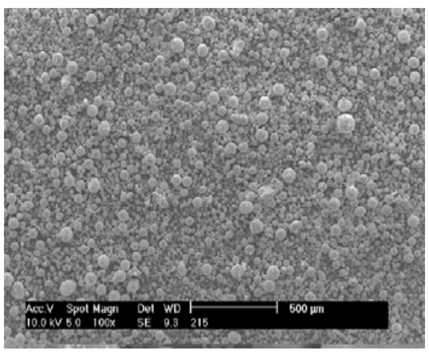


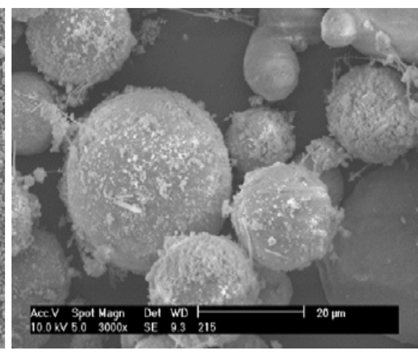


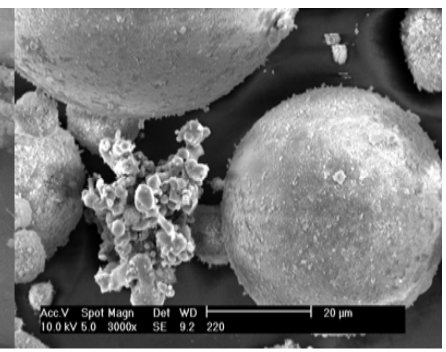


300x *1000x* *5000x*

S06-215 – after plasma processing



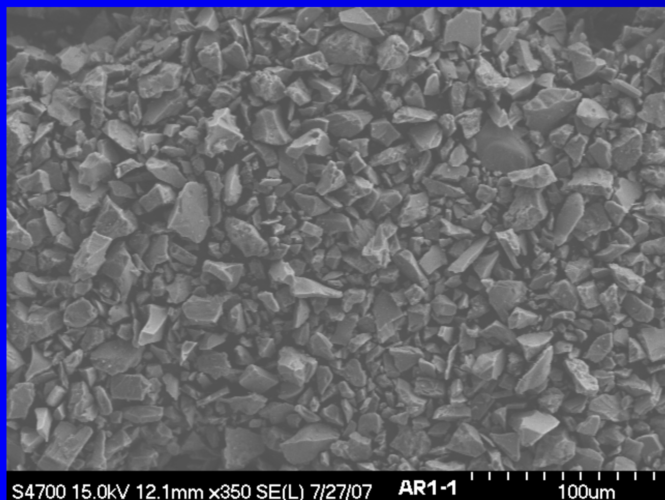


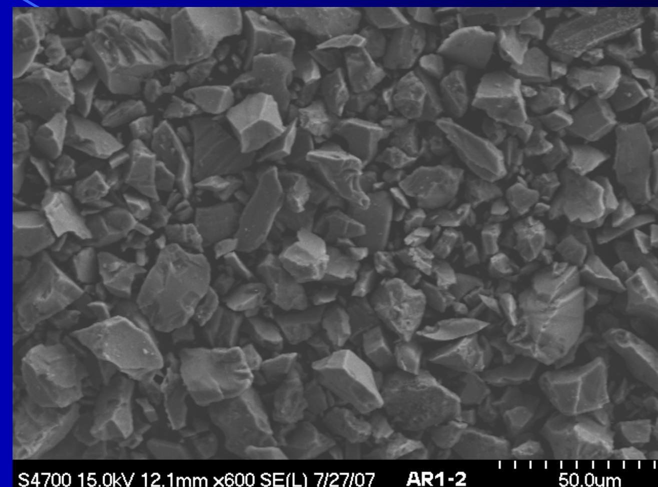


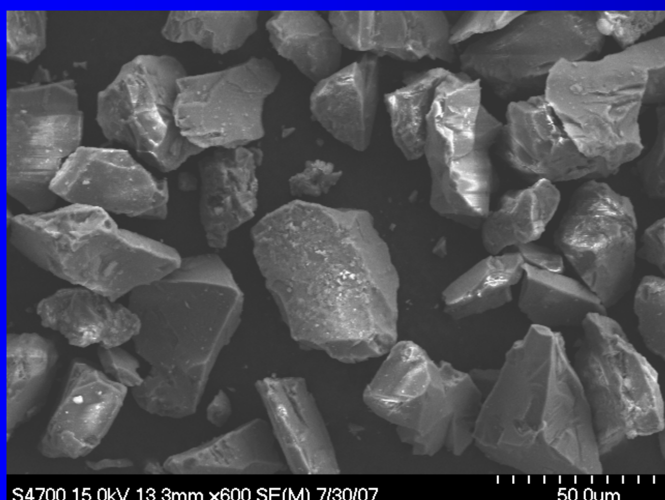
100x *3000x* *3000x*

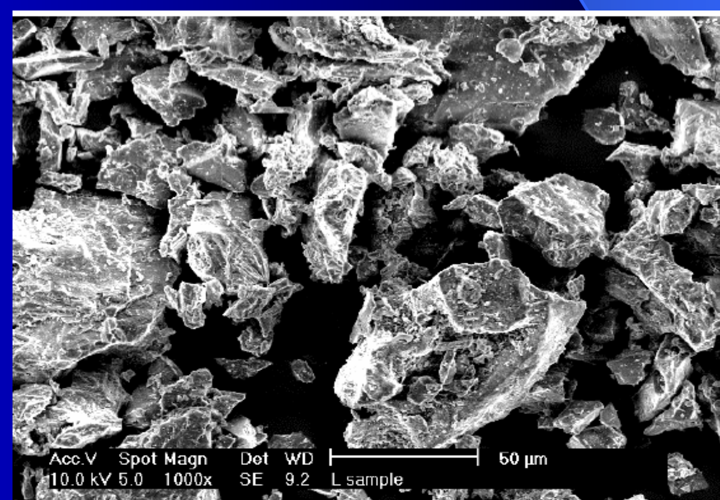
As-received and plasma processed (S06-215) lunar regolith simulant (JSC-1) at several magnifications showing spherical and agglutinate morphology.

JSC-1A Simulant (As-Received) vs. JSC-1



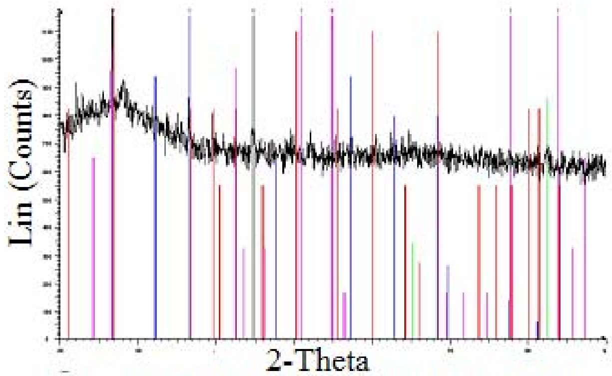




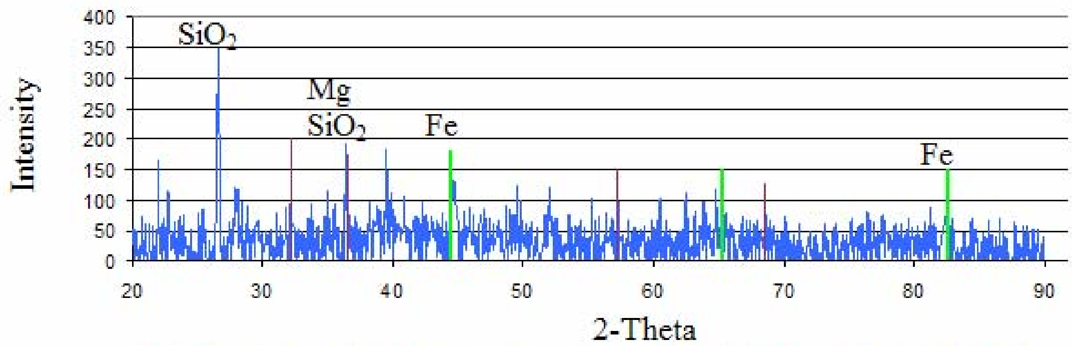


JSC-1

Lunar Regolith Simulant



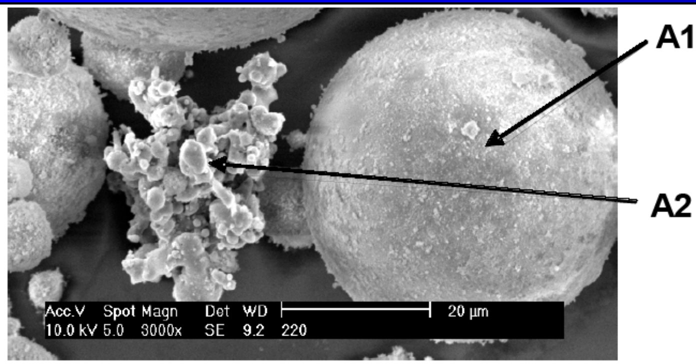
(a) XRD of plasma processed JSC-1.



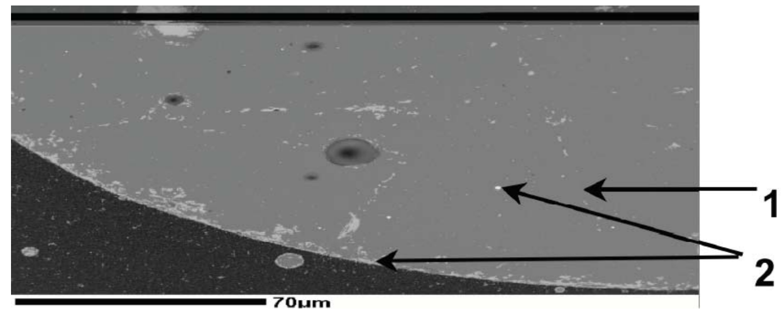
(b) XRD of plasma processed JSC-1 after background reduction.

(a) XRD pattern of plasma processed JSC-1 simulant showing predominant presence of amorphous or glassy phase and (b) after background reduction shows the presence of graphite (C), Fe (bcc), Mg, and hexagonal quartz (SiO_2), and potentially additional reduced metallic species in a non-crystalline state.

Agglutinate & Volcanic Glass Analogue Particles



(a)



(b)

	Spot number	Mg	Al	Si	Ca	Fe	Ti	O (balance)	Total
Agglutinate (*(a)* A2) and (b)	*(b)* 1 Matrix	3.330	9.880	21.900	8.460	6.790	1.080	48.380	100
	(b) 2 Bright spots	3.090	0.960	21.480	0.530	68.740	0.700	4.500	100
Spherical Particle (*(a)* A1)	1	0.001	10.380	34.110	0.015	0.072	0.004	55.410	100
	2	2.076	4.010	16.330	6.630	5.110	0.738	65.110	100
	3	3.450	4.630	16.740	6.930	7.140	1.349	59.760	100
	4	3.810	7.660	22.820	8.340	8.930	1.284	47.150	100
	5	0.787	4.810	12.250	3.790	10.890	0.632	66.850	100

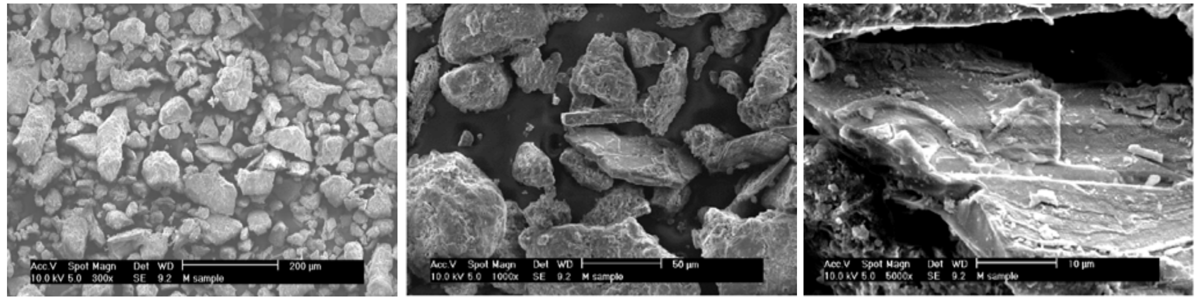
EDS analysis of S06-215 showing elemental iron on agglutinate surface (a – A2) and dispersed within agglutinate (b – 2). Shown in view (a) (3000x) are spherical particles similar to lunar volcanic glass (A1) and agglutinate similar to lunar agglutinates (A2). View (b) is a cross sectional view of a particle similar to A2 showing elemental iron on the surface of the agglutinate and dispersed within it (arrow 2) and the matrix material (arrow 1).

Assessment of Additives to Improve Lunar Regolith Simulant

- Simulant particles were produced during Phase 1 with morphology very similar to lunar agglutinates and volcanic glasses
- Micron sized Fe observed on particle surfaces and interiors – will determine if nano-size Fe is also present during Phase 2
- Restoration of angular/faceted surfaces
- Creation of different size agglutinates
- Glassy phase / agglutinate separation
- Define processing parameters needed to produce either type of particle during Phase 2
- Combine with JSC-1A Standard to produce mature soil simulant.
- Characterization of mature simulant (composition, morphology, hardness, grain interlocking of bulk soil, cohesion, ect.)
- Plasma processing is rapid, low cost, and high-volume.

JSC Mars-1 Martian Regolith Simulant

As-Received Martian Soil Simulant (JSC MARS-1)



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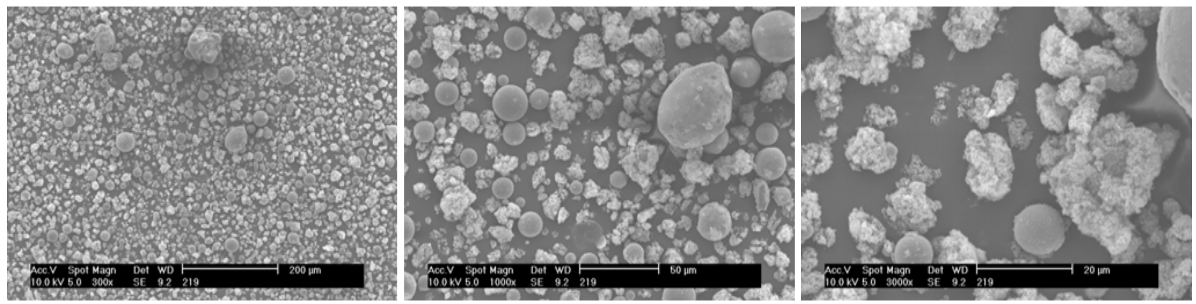
S06-219



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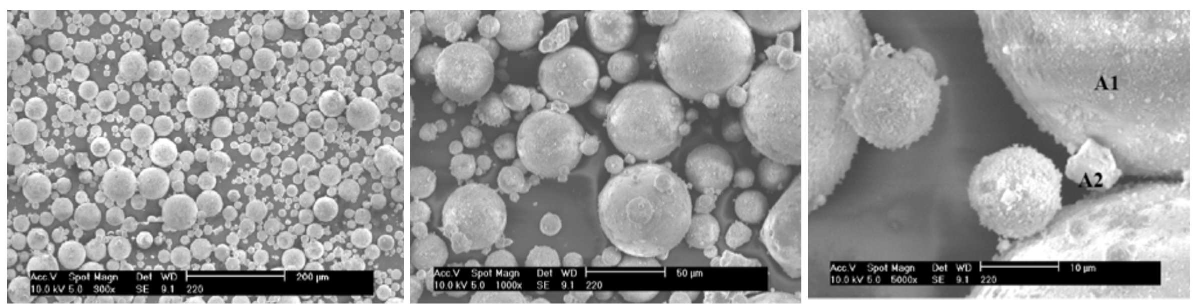
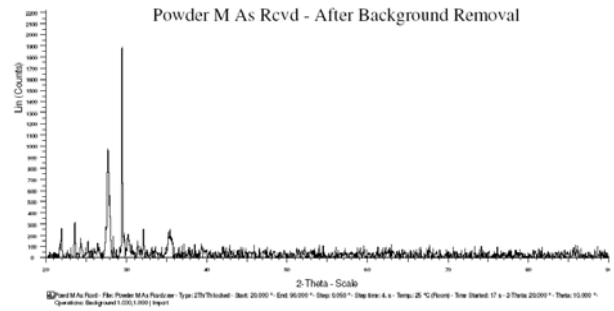
S06-220



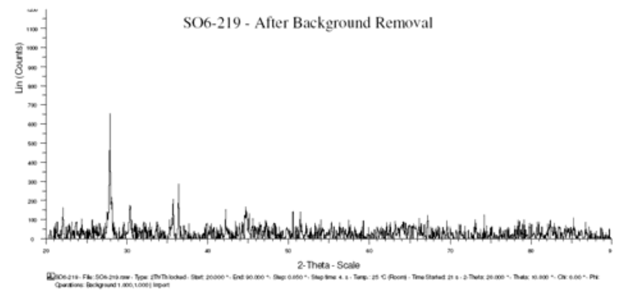
300x *1000x* *5000x*

SEM images of as-received MARS-1 simulant compared to S06-219 and S06-220 processed simulant. The differences in processed particle morphology compared to the as-received simulant are quite pronounced.

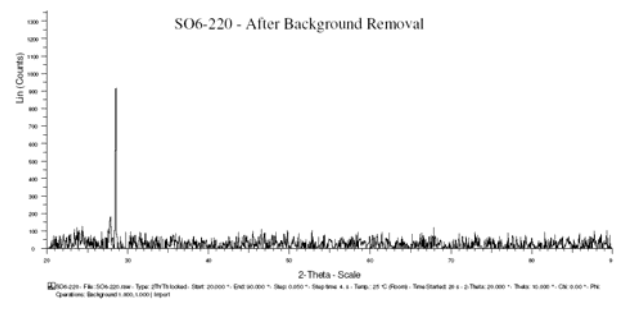
JSC Mars-1 Martian Regolith Simulant XRD Analysis



(a)



(b)



(c)

XRD analysis of as-received MARS-1 simulant compared to S06-219 and S06-220 processed simulant. MARS-1 as-received powder (a) presents a complicated XRD pattern. Minerals that may be present include albite ($NaAlSi_3O_8$), magnetite (Fe_3O_4), labradorite ($Na_2O{\circ}2CaO{\circ}3Al_2O_3{\circ}8SiO_2$), and magnesioferrite ($MgFe_2O_4$). Some peaks could not be matched with minerals existing in the database. Crystalline phases present in S06-219 (b) include Fe(bcc), magnesioferrite ($Mg\ Fe_2O_4$), and SiO_2 (hexagonal quartz), while those present in S06-220 (c) include Si and SiO_2 (hexagonal quartz). (c) is mostly amorphous.

Phase 2 Technical Objectives

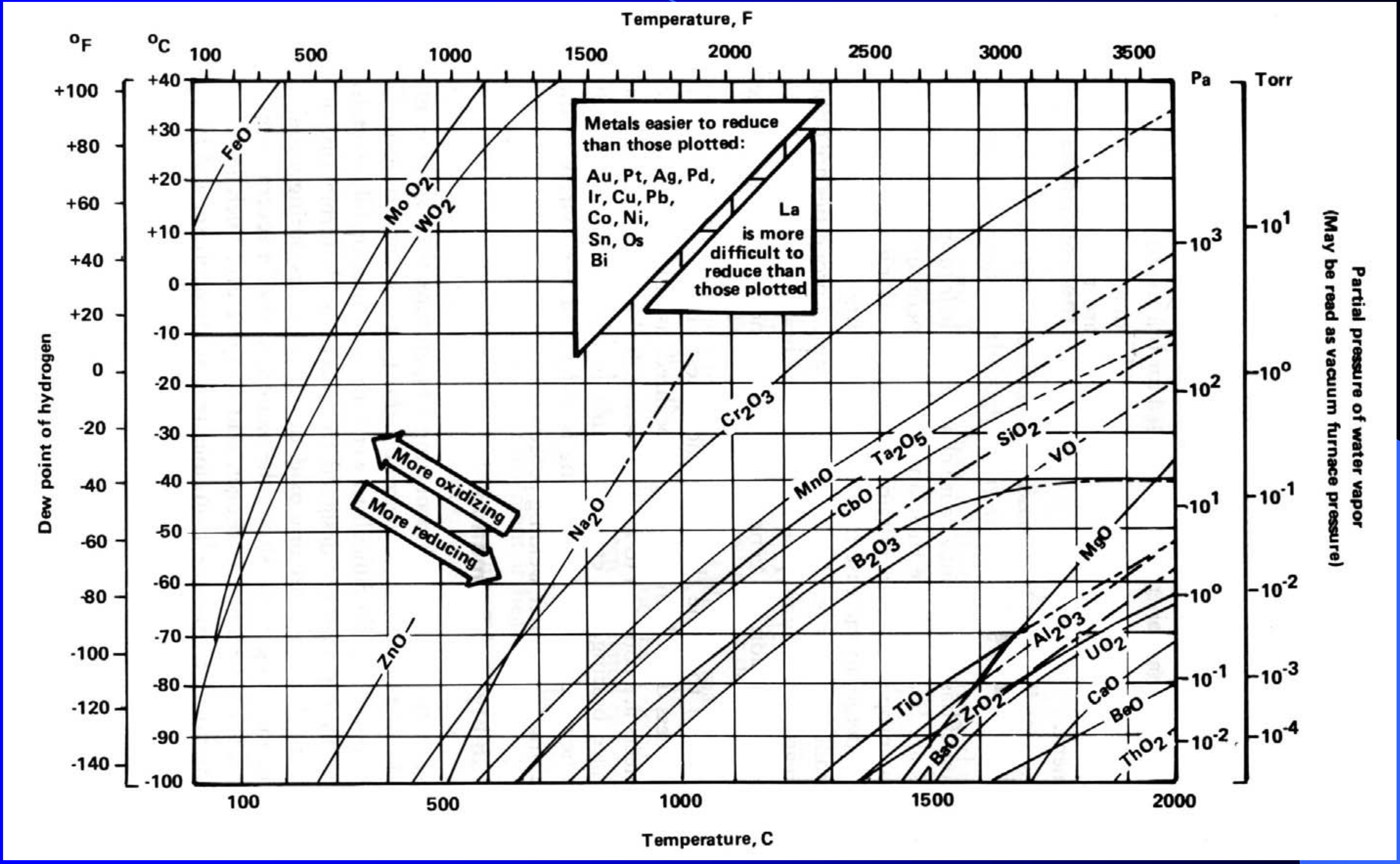
- Collect free O_2 gas from plasma processing gas stream.
- Produce & quantify/characterize additional metals (Ti, Al, & Ca) from plasma processing.
- Measure, record, and optimize plasma processing parameters using real-time temperature and velocity data along with theoretical calculations to evolve O_2 and metals.
- Minimize power requirements for the system
- Investigate low pressure processing to simulate lunar environment.
- Develop initial design for 1/5 scale prototype system suitable for testing on a robotic mission.
- Produce agglutinates and volcanic glass analog particles that when combined with the current JSC-1A material create a mature lunar regolith simulant suitable for dust, abrasion, tool wear and mining research.

Theoretical Calculations

Dr. Subhayu Sen, BAE Systems

- Gibbs Energy Minimization used to aid in selection of plasma parameters.
- Particle / plasma temperature and processing atmosphere determine products produced.
- Evaluate effects of higher processing temperatures (>3000C) and low pressure atmospheres (<10-3 torr) on plasma reduction.
- Confirm calculations through experimentation.

Metal-Metal Oxide Equilibrium as a Function of Temperature and Pressure



Metallic Species Characterization / Future Work

- Processed powders are being investigated to determine if they contain nano-size particles, particularly Fe, as this could make further processing via microwave or molten salt electrolysis attractive
- Separation techniques for finished particles by composition and size (slurry, fluidized bed, gravity, magnetism, static charge) and gas transport of particles will be investigated.
- Conventional analysis:
  – XRD – crystalline metals and indication of amorphous powders
  – SEM and optical microscopy – particle morphology, metallic and oxide components,
  – TEM and metallurgical techniques – interior of the particles

Design Development for 1/5 Scale Prototype

- Subscale processing system will be designed for demonstration during future robotic mission
- Currently, plasma technology can be miniaturized to some extent
- Amount of metals needed is not yet determined
- Multifunctional system capable of producing both oxygen and metals by changing only the processing parameters. (Mainly oxygen use)
- Minimization of power requirements, alternate power sources, such as a solar concentrator

NASA Requirements

		Oxygen Production	Mass of System	Power Consumption
NASA Requirements	**2006 SBIR Solicitation**	9 MT/yr	?	0.5 kW average power
	MoonROx Centennial Challenge	1:40 O2:Regolith (g) at a rate of 625 g O2 per hr	50 kg	2.5 kW/hr
Design Goals	**1/5 Scale Design**	1.8 MT	<100 kg	0.5 kW average power
	1/10 Scale Design	0.9 MT	<100 kg	0.5 kW average power

Phase 1 Final Results

- Phase 1 demonstrated feasibility of plasma reduction for producing of
  - metallic powders for in-situ space fabrication
  - critical gases such as CO and oxygen to support habitat and propulsion applications
- Theoretical calculations were used to predict the evolution of gases and the production of metals from plasma reduced lunar regolith. Experimental results confirmed the thermodynamic predictions.
- XRD and microprobe analyses demonstrated crystalline metals (Si, Fe and Mg) were produced from plasma reduced regolith. Amorphous material was also produced.

Phase 1 Final Results

- Agglutinate and spherical phases similar to lunar agglutinates and volcanic glass have been obtained. These can be added to current bulk JSC-1A to produce a more realistic lunar simulant for studying friction, tool wear, excavation techniques, and dust mitigation technologies.
- Micron-size Fe has been identified on the surface and within agglutinate and spherical particles of processed JSC-1. These particles increase the similarity of the processed material to actual lunar regolith particles. There is a high probability that nanosize particles will be found in the processed material during Phase 2.
- Typical production rates = up to 460 lbs/day with current setup.

Further Information

- " Plasma Processing of Lunar Regolith Simulant for Diverse Applications" *to be presented at* STAIF 2008 (Space Technology and Applications International Forum) – Feb 10-14, Albuquerque, NM
- Phase 1 Final Report for NNM07AA23C

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